

Battery-Aware Relay Selection for Energy Harvesting Cooperative Networks

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Abstract—The use of energy harvesting (EH) nodes as cooperative relays is an emerging solution for enabling green wireless systems. In this paper, we consider multiple EH relay nodes harvesting energy from the radio frequency (RF) signal received from the source and use that harvested energy to forward the source information to the destination. Unlike conventional relays with fixed power supplies, EH relays may not be permanently available to assist the source transmission due to the limited energy conversion efficiency, the mismatch between the charging and discharging profiles, and the finite energy storage capacity. We propose the battery-aware relay selection (BARS) scheme, which jointly considers the channel condition and the battery status for relay selection. The outage probability of the proposed scheme is analyzed using a Markov chain model. Simulations are performed to validate the analysis accuracy. Through numerical results, we show that the proposed BARS scheme can achieve full diversity order equal to the number of relays without the need of fixed power cables.

I. INTRODUCTION

Powering wireless devices by sustainable energy is an emerging solution to enable green wireless networks [1]. Known as energy harvesting (EH), passively powered devices collect energy from external power sources, such as vibration, solar, thermoelectric effects, ambient radio frequency (RF) radiation, and so forth, to maintain their physical operations without any wiring cost. In this work, we are interested in EH based on RF signals [2].

One of the potential applications of EH nodes is the cooperative relays, which are deployed to extend network coverage and improve transmission reliability between two distant nodes. Traditionally, relays are powered by fixed power supplies, leading to extra power consumption for information relaying. It is thus desirable to replace traditional relays by EH relays that power themselves by the energy harvested from the source signal as a green communication solution. In this context, no additional power is consumed to perform information relaying but the key challenge is that these EH relays may not be permanently available to help as their traditional counterparts. When more EH relays are short of enough energy to transmit, it implies less diversity branches can be used to pass the source information, leading to low diversity gain.

Several practical constraints hinder the EH relays from being useful to cooperate. Firstly, only a portion of the harvested

energy is available to use, because the energy collected by the energy harvester circuit needs to be converted to DC voltage first. Depending on the conversion circuit design, the energy conversion efficiency reported in the literature varies from 30% ~ 50% [3], [4]. Since the harvested energy from a single shot may be far from enough to be used for transmission, it is desirable to accumulate the harvested energy by storing it in an energy storage such as a rechargeable battery or a super capacitor for the later use. In practice, the energy storage is limited in size, and thus EH relays may encounter energy shortage whenever the energy consumption rate is higher than the energy harvesting rate. One countermeasure is thus to select those relays with sufficient energy to cooperate via a certain relay selection scheme.

Relay selection has been extensively addressed for conventional relays. Previous research indicates that selecting one relay with the superior channel condition than the others is promising in achieving the same diversity-multiplexing tradeoff as that by using sophisticated space-time coding schemes [5], [6]. Such a relay selection scheme, referred to channel state information (CSI)-based scheme, may fail to fully exploit the diversity gain if the selected relay lacks of sufficient power to transmit and thus it is not suitable to cooperative networks with EH relays. In [7], the CSI-based relay selection is applied to cooperative networks where EH relays are subject to finite energy storage and limited energy conversion efficiency. It is shown that the CSI-based relay selection scheme does not achieve any diversity gain even with a large battery. In [8], the authors consider two relay selection schemes, namely the random relay selection and the distance-based relay selection schemes, in cooperative networks with EH relays. Their analysis shows that the diversity gain achieved by these two methods is at most two. The analysis conducted in [9] further reveals that the diversity gain achieved by the CSI-based relay selection scheme using EH relays is only half of that using traditional relays.

In this work, we propose a new relay selection for EH relays. The proposed scheme, referred to as battery-aware relay selection (BARS), employs both CSI and battery status for making the relay selection decision. We analyze the outage probability of BARS by developing a Markov-chain model that captures the evolution of battery status at each relay selection

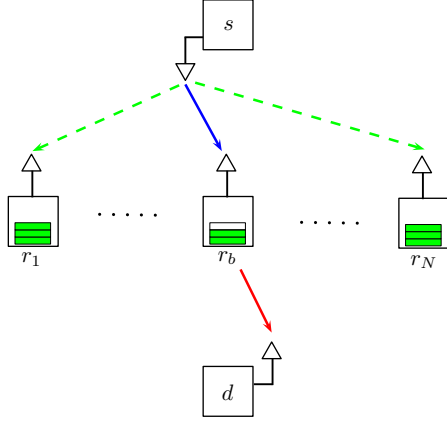


Fig. 1. A two-hop cooperative communication network with multiple relays powered by the energy harvested from the source signal.

epoch. Numerical results are presented to validate the analysis accuracy and demonstrate the performance of the proposed relay selection scheme with EH relays subject to numerous system parameters. The rest of this paper is organized as follows. Sec. II explains the system model. The traditional CSI-based and the proposed relay selections schemes are introduced in Sec. III. Performance analysis is conducted in Sec. IV, followed by numerical results in Sec. V. Concluding remarks are drawn in Sec. VI.

II. SYSTEM MODEL

Consider a multi-relay network with one source s , one destination d , and N relays r_1, \dots, r_N , as shown in Fig. 1. The communication between s and d relies on the intermediate relays that perform decode-and-forward (DF) to forward the source information, assuming that the direct link between s and d is not available. In this work, the RF signal emitted by s is the sole energy source for relays. The harvested energy is stored in a rechargeable battery of size B by converting the RF signal into the DC voltage. The conversion efficiency is characterized by the parameter $\kappa \in [0, 1]$. The battery size is assumed to be identical for all relays, and a discrete battery model is employed. Specifically, each relay battery is quantized into L levels. Let b_l denote the l th quantization level for $l = 0, 1, \dots, L+1$. The battery level associated with relay r_i , denoted as V_i , corresponds to level l if $V_i \in (b_l, b_{l+1}]$ with $b_0 = 0$ and $b_{L+1} = B$. The battery is assumed to be linear such that the charging and discharging rates are constant.

The source transmit with a fixed power P , while relay r_i transmit power P_{r_i} is adjusted to ensure the successful decoding at the destination. To support the transmission rate of R bits/sec/Hz, the decoding threshold T equals $2^{2R} - 1$. Hence the minimum transmit power required for successful decoding by d is $P_{r_i} = T/h_i$, where h_i denotes the channel gain power between r_i and d . The harvested energy from the source transmission at relay r_i is $E_i = P g_i \kappa$, where g_i is the channel gain power between s and r_i . Assuming Rayleigh fading channels, both g_i 's and h_i 's are exponentially

distributed with mean \bar{g}_i and \bar{h}_i , respectively. In addition, the thermal noise power N_0 at the receiving end is assumed to be identical for all nodes. Therefore, the signal-to-noise ratio (SNR) P/N_0 is a constant.

III. RELAY SELECTION

We first review the CSI-based relay selection scheme for conventional relays. Considering DF relays, define the set of relays that can decode successfully as the decoding set, i.e., $\mathcal{D}(s) = \{r_i | \frac{P_s g_i}{N_0} \geq T\}$. From this decoding set, the best relay, denoted as r_b^{CSI} , is chosen as the one with the superior relay-destination channel condition than the others. Such a CSI-based relay selection scheme can be expressed as

$$r_b^{\text{CSI}} = \arg \max_{r_i \in \mathcal{D}(s)} h_i. \quad (1)$$

This scheme is recognized as the optimal diversity-achieving relay selection scheme because it achieves the same diversity gain as using multiple relays to forward the source signal but consuming much less radio resources. For EH relays with finite energy storage, however, the selected relay according to (1) might lack of enough power to transmit, yet its channel condition is the best.

To overcome this drawback, we propose to select the cooperating relay with battery status taking into account. To this end, we first define a subset of relays that not only can decode the source information but also has sufficient power to transmit. Such a set of relays is referred to as the forwarding set defined as

$$\mathcal{F}(s) = \left\{ r_i \mid \left(\frac{P_s g_i}{N_0} \geq T \right) \cap (V_i \geq P_{r_i}) \right\}, \quad (2)$$

where V_i is the current battery level of relay r_i at the selection epoch. Given the forwarding set, the best relay selected by the proposed scheme, referred to as battery-aware relay selection (BARS), can be expressed as

$$r_b^{\text{BARS}} = \arg \min_{r_i \in \mathcal{F}(s)} E_i, \quad (3)$$

where $E_i = P_s g_i \kappa$ is the harvested energy by relay r_i . The rationale behind BARS is two-fold. Firstly, selecting the best relay from the forwarding set ensures that the selected relay can successfully decode the source information and has sufficient power to transmit. This is important to fully exploit the selection gain provided by multiple relays based on energy harvesting. Secondly, by choosing the relay with the minimum harvested energy in the forwarding set, the accumulated amount of harvested energy per source transmission is maximized because there are always at least $N - 1$ relays performing energy harvesting (it is possible that all the N relays will harvest energy if the forwarding set is empty).

We note that although we do not have a rigorous proof for the achievable diversity gain of BARS, the numerical results shown in Sec. V reveal that BARS is plausible to achieve full diversity order equal to the number of available relays. The key to this success lies in the consideration of the forwarding set $\mathcal{F}(s)$ in relay selection. If we replace the role of $\mathcal{F}(s)$ in

the selection rule (3) by $\mathcal{D}(s)$, i.e., ignoring the battery status, full diversity gain is not guaranteed. The modified scheme, referred to the benchmark scheme, can be expressed as

$$r_b^{\text{Benchmark}} = \arg \min_{r_i \in \mathcal{D}(s)} E_i, \quad (4)$$

and its performance will be discussed in Sec. V.

IV. PERFORMANCE ANALYSIS

In BARS, the outage event occurs only when all the relays are in the harvesting mode, i.e., the forward set $\mathcal{F}(s)$ is empty. From (2), whether a relay performs energy harvesting or data forwarding depends on both its battery status and the channel conditions. Based on the discrete battery model, the battery of an arbitrary relay may be in one of the $L+2$ levels and there are total of $(L+2)^N$ combinations of battery status for N relays. Denote $s_j = (V_1, V_2, \dots, V_N)$ as the j th combination, where $V_i = \{0, \dots, L+1\}$ for $i = 1, \dots, N$. The outage probability of BARS can be expressed in the following general form as

$$P_{\text{out}} = \sum_{j=1}^{(L+2)^N} \Pr[\mathcal{F}(s) = \emptyset | s_j] \Pr[s_j]. \quad (5)$$

In (5), the conditional probability, $\Pr[\mathcal{F}(s) = \emptyset | s_j]$ depends on the specific configuration of s_j and thus there is no general form. On the other hand, the probability $\Pr[s_j]$ can be obtained by modeling the charging/discharging behavior of each relay battery status as a discrete-time Markov chain (DTMC) with finite states. The transition probability of the DTMC is defined as $\mathbf{P} = [p_{j,k}]$ where $p_{j,k}$ denotes the transition probability from state s_j to state s_k . It can be verified that \mathbf{P} is irreducible and row stochastic, and thus there exists a unique steady-state probability vector $\boldsymbol{\pi} = \{\pi_j\}_{j=1}^{(L+2)^N}$, where $\pi_j = \Pr[s_j]$. Again, \mathbf{P} does not have a general expression but can be obtained explicitly given the numbers of relays and battery levels. In the following, we first derive the battery state transitions of an arbitrary relay, which serve as the basis for constructing \mathbf{P} . To ease the presentation, $F_X(\cdot)$ represents the CDF of a random variable X .

A. Battery State Transitions of An Arbitrary Relay

For convenience, define $A_f(m)$ the event that a relay with battery state V_m is in the forwarding mode. According to (2), $A_f(m) \triangleq (Pg_i/N_0 \geq T) \cap (b_m \geq P_{r_i})$ with probability

$$\Pr[A_f(m)] = (1 - F_{g_i}(\frac{TN_0}{P}))(1 - F_{h_i}(\frac{T}{b_m})) \quad (6)$$

Similarly, denote the event of a relay with battery state V_m is in the charging mode mode by $A_c(m) \triangleq (b_m < P_{r_i}) \cup [(b_m \geq P_{r_i}) \cap (Pg_i/N_0 < T)]$ with probability

$$\Pr[A_c(m)] = F_{h_i}(\frac{T}{b_m}) + \left[1 - F_{h_i}(\frac{T}{b_m})\right] F_{g_i}(\frac{TN_0}{P}). \quad (7)$$

1) $m = n$ for $0 \leq m < L+1$: The relay battery level remains unchanged if the relay r_i is in the charging mode but

the collected energy does not increase the battery level with probability

$$\begin{aligned} p_{m,m} &= \Pr[A_c(m) \cap (b_m \leq b_m + Pg_i\kappa < b_{m+1})] \\ &= \Pr[(b_m < P_{r_i}) \cap (g_i < \frac{b_1}{P\kappa})] \\ &\quad + \Pr[((b_m \geq P_{r_i}) \cap (\frac{Pg_i}{N_0} < T)) \cap (g_i < \frac{b_1}{P\kappa})] \\ &= F_{g_i}(\frac{b_1}{P\kappa}) F_{h_i}(\frac{T}{b_m}) + \begin{cases} F_{g_i}(\frac{TN_0}{P}), & T < \frac{b_1}{\kappa}, \\ F_{g_i}(\frac{b_1}{P\kappa}), & T \geq \frac{b_1}{\kappa} \end{cases} \\ &\triangleq Q_1(m). \end{aligned} \quad (8)$$

2) $m = 0, n = L+1$: Given the battery is empty, relay r_i must be in the charging mode. The probability that the relay battery becomes fully charged is identical to

$$\begin{aligned} p_{0,L+1} &= \Pr[Pg_i\kappa \geq B] = 1 - F_{g_i}(\frac{\alpha}{\kappa}) \\ &\triangleq Q_2(0, L+1). \end{aligned} \quad (9)$$

3) $m = 0, 0 < n < L+1$: In this case relay r_i with an empty battery harvests energy from the received signal such that its battery becomes partially charged. This transition probability is equal to

$$\begin{aligned} p_{0,n} &= \Pr[b_n \leq Ph_i\kappa < b_{n+1}] = F_{g_i}(\frac{b_{n+1}}{P\kappa}) - F_{g_i}(\frac{b_n}{P\kappa}) \\ &\triangleq Q_3(0, n). \end{aligned} \quad (10)$$

4) $0 < m \leq L+1, n < m$: The relay battery level is reduced from level m to level n only if the relay is in the forwarding mode. Hence, the transition probability can be found as

$$\begin{aligned} p_{m,n} &= \Pr[A_f(m) \cap (b_n \geq b_m - P_{r_i} < b_{n+1})] \\ &= \left[1 - F_{g_i}(\frac{TN_0}{P})\right] \left[F_{h_i}(\frac{T}{b_m - b_{n+1}}) - F_{h_i}(\frac{T}{b_m - b_n})\right] \\ &\triangleq Q_4(m, n). \end{aligned} \quad (11)$$

5) $0 < m \leq L+1, n = L+1$: The partially charged relay battery becomes fully charged if the relay is in the charging mode and the amount of harvested energy exceeds the remaining space of the battery, whose probability is given by

$$\begin{aligned} p_{m,L+1} &= \Pr[A_c(m) \cap (Pg_i\kappa \geq B - b_m)] \\ &= F_{h_i}(\frac{T}{b_m}) \left[1 - F_{g_i}(\frac{\alpha P - b_m}{P\kappa})\right] \\ &\quad + \begin{cases} 0, & T \leq \frac{\alpha P - b_m}{\kappa}, \\ F_{g_i}(\frac{TN_0}{P}) - F_{g_i}(\frac{\alpha P - b_m}{P\kappa}), & T > \frac{\alpha P - b_m}{\kappa} \end{cases} \\ &\triangleq Q_5(m, L+1). \end{aligned} \quad (12)$$

6) $0 < m < n < L+1$: This corresponds to the case that the non-empty battery remains not full after harvesting

the energy, which takes place with probability

$$\begin{aligned}
p_{m,n} &= \Pr[A_c(m) \cap (b_n < b_m + P g_i \kappa < b_{n+1})] \\
&= F_{h_i}\left(\frac{T}{\kappa}\right) \left[F_{g_i}\left(\frac{b_{n+1}-b_n}{P\kappa}\right) - F_{g_i}\left(\frac{b_n-b_m}{P\kappa}\right) \right] \\
&+ \begin{cases} 0, & T < \frac{b_n-b_m}{\kappa}, \\ F_{g_i}\left(\frac{TN_0}{P}\right) - F_{g_i}\left(\frac{b_n-b_m}{P\kappa}\right), & \frac{b_n-b_m}{\kappa} \leq T < \frac{b_{n+1}-b_m}{\kappa}, \\ F_{g_i}\left(\frac{b_{n+1}-b_m}{P\kappa}\right) - F_{g_i}\left(\frac{b_n-b_m}{P\kappa}\right), & T \geq \frac{b_{n+1}-b_m}{\kappa} \end{cases} \\
&\triangleq Q_6(m, n). \tag{13}
\end{aligned}$$

7) $m = n = L + 1$: This case arises only when the relay is in the charging mode with probability

$$p_{L+1,L+1} = \Pr[A_c(L+1)] \triangleq Q_7(L+1), \tag{14}$$

where $\Pr[A_c(L+1)]$ has been given in (7).

B. Transition Probability Matrix

Based on the state transition probabilities obtained in the previous subsection, the transition probability matrix of the DTMC can be constructed. Since the number of states grows exponentially with the number of relays, a systematic approach is provided below to facilitate the construction of the transition probability matrix.

- Step 1: Identify all the possible combinations of the forwarding set $\mathcal{F}(s)$. Given N relays, there are 2^N different configurations of $\mathcal{F}(s)$.
- Step 2: For each $\mathcal{F}(s)$, find the associated transition probabilities. For example, if $L = 1$ and $N = 2$, there will be 2^2 combinations of $\mathcal{F}(s)$. Consider $\mathcal{F}(s) = \{r_1\}$, one of the potential state transitions is from $(1, 0)$ to $(0, 0)$ where r_1 's battery level is reduced by one level with probability $Q_4(1, 0)$ and r_2 's battery remains empty with probability $Q_1(0)$.
- Step 3: Once the transition probability matrix \mathbf{P} is obtained, the steady-state probabilities can be obtained by solving the balanced equation $\boldsymbol{\pi} \mathbf{P} = \boldsymbol{\pi}$ along with the normalized condition $\sum_{m=1}^{(L+2)^N} \pi_m = 1$

V. RESULTS AND DISCUSSIONS

This section presents numerical results to demonstrate the performance of the proposed BARS scheme. Unless specified, the following parameters are used throughout this section: $R = 1$ bits/Sec/Hz, $N_0 = 1$, and $\bar{g}_i = \bar{h}_i = 1$. In simulations, all relay batteries are set to be full initially. Each curve in the figure is obtained from 10^6 independent runs. Besides, we use ‘‘Theo’’ and ‘‘Sim’’ to indicate the theoretical and simulation results, respectively.

Fig. 2 shows the outage probability of BARS versus SNR under different number of relays N and the number of battery quantization levels L . Here we fix the battery scaling factor $\alpha = 1$ and the energy conversion efficiency $\kappa = 0.5$. For $L = 1$, both theoretical and simulation results are included while only simulation results are shown for $L = 100$. It can be seen that the theoretical results agree with the simulated ones well. When $L = 1$, the outage probability decreases with N but incurs a severe error floor at high SNR. This is because a small

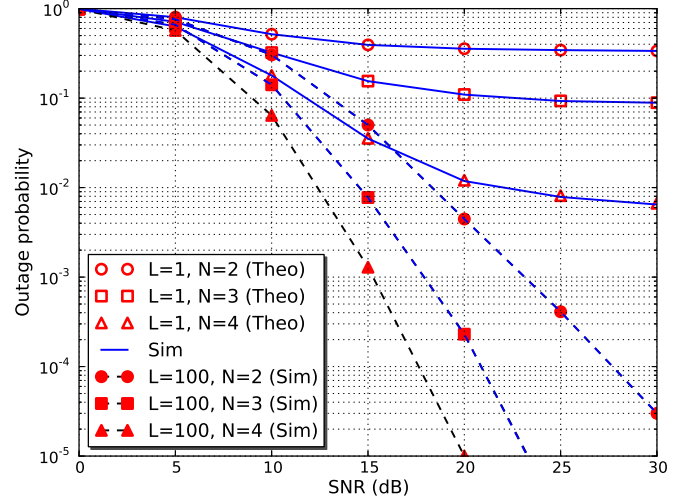


Fig. 2. Outage probability of BARS under varied L and N with fixed $\kappa = 0.5$.

L implies a lossy quantization interval. In this case, the amount of stored energy can hardly reach the quantization threshold and thus the battery is often at the low level. This problem can be resolved by increasing L that in turns reduces the risk of no relays eligible to help. As L increases to 100, the slope of the outage probability curve is equal to the number of relays N , which suggests that BARS can fully explore diversity gain provided with sufficient battery quantization levels.

Fig. 3 investigates the impact of energy conversion efficiency κ for $N = 3$. Intuitively, the outage probability decreases with increasing κ , but the decreasing trend is less significant when L is large. This is because a larger L implies a finer granularity of the battery level such that the battery status is not sensitive to κ . For $L = 10$ and 100, the outage performance of BARS is nearly saturated at $\kappa = 0.5$, which is about the practical value of most RF energy harvesters. In other words, the room for further improvement by more sophisticated energy harvester might not be as notable as expected.

The impact of battery size to the outage performance is explored in Fig. 4 by varying the battery scaling factor α . Here, we set $L = 100$, $\kappa = 0.5$, SNR = 20 dB, $R = 2$ bits/sec/Hz, and only simulation results are shown. It follows the intuition that increasing the battery size helps to reduce the outage probability, but the gain becomes diminished when $\alpha > 0.6$, regardless of the number of relays N . This can be explained by the fact that when the battery is larger than a certain degree, it is less likely to be fully charged given a limited energy conversion efficiency. On the other hand, the impact of battery size is more significant when N is larger, as a consequence of selection diversity.

Finally, we compare the performance of BARS with the CSI-based relay selection scheme in (1) and the benchmark scheme in (4). In Fig. 5, we fix $\kappa = 0.5$ and consider $N = 2$ and 3. One can see the significant improvement of BARS over the CSI-based and the benchmark relay selection schemes,

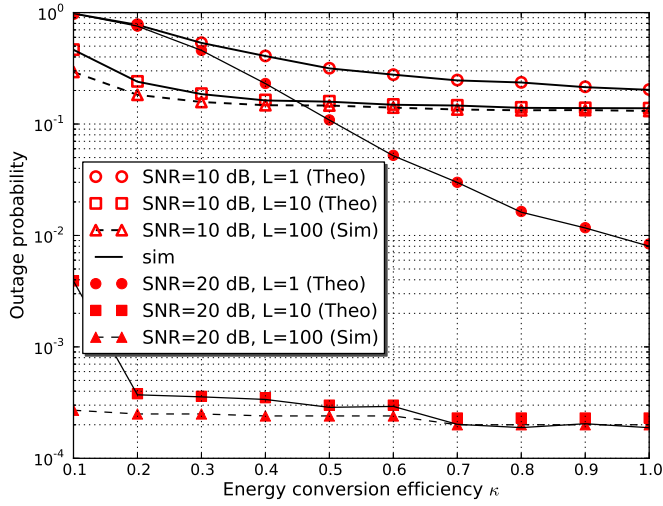


Fig. 3. Outage probability of BARS vs. energy conversion efficiency κ under varied L and SNR for $N = 3$.

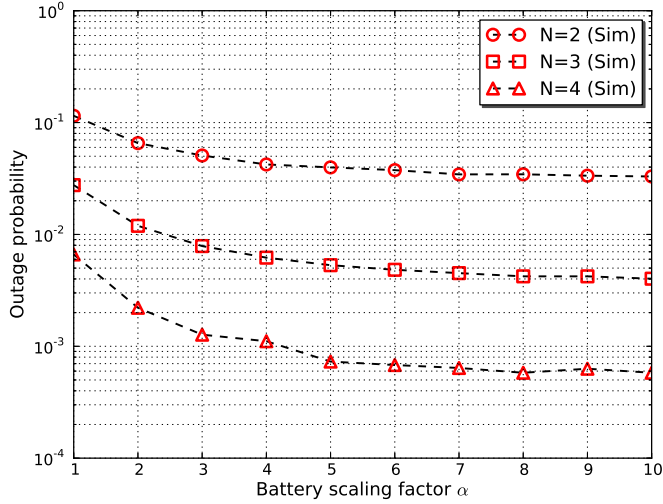


Fig. 4. Outage probability of BARS vs. battery scaling factor α under varied N with $L = 100$, $\kappa = 0.5$, SNR=20 dB, and $R = 2$ bits/sec/Hz.

both failing to achieve full diversity gain. We note that the diversity order of BARS shown in the graph is slightly less than N primarily because a small quantization resolution of the battery is used ($L = 10$). BARS can achieve full diversity order provided with $L = 100$, as shown in Fig. 2.

VI. CONCLUSION

In this paper, we proposed a relay selection scheme called BARS for EH relays. BARS differs from traditional relay selection schemes based on CSI in that it takes into account the battery status of relays in order to prevent selecting the relay lacking of energy to forward the source signal, a key factor that deteriorates the performance of EH relays with finite battery. In BARS, the relays that can decode the source information and have sufficient power to transmit are defined as the forwarding set. In this set, the best relay is chosen

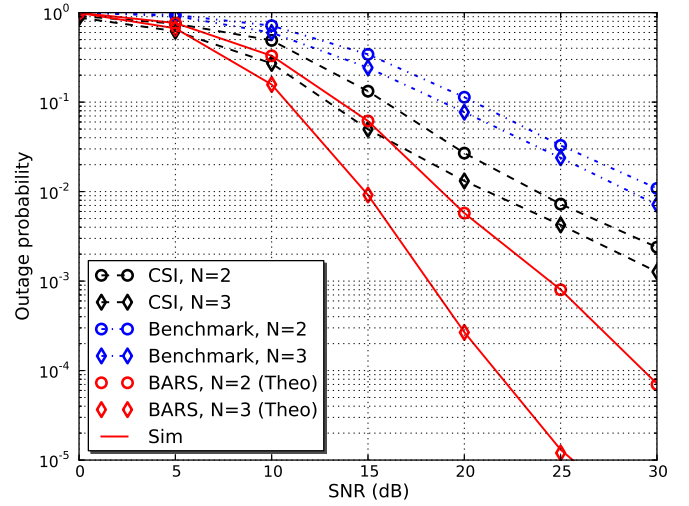


Fig. 5. Comparison of outage probabilities for BARS and CSI-based relay selection with $L = 10$ and $\kappa = 0.5$.

as the one that has the least harvested energy, depending on the source-relay channel condition and the energy conversion efficiency of the energy harvester. Such a selection allows the network to collect the largest amount of harvested energy per source transmission. The performance of BARS is analyzed theoretically based on a discretized battery model. Our results reveal that BARS achieves full diversity order and significantly outperforms the traditional CSI-based relay selection scheme, which fails to fully exploit diversity gain provided by multiple EH relays.

REFERENCES

- [1] L. X. Cai, H. V. Poor, Y. Liu, T. H. Luan, X. S. Shen, and J. W. Mark, "Dimensioning network deployment and resource management in green mesh networks," *IEEE Wireless Commun.*, vol. 18, no. 5, pp. 58–65, Oct. 2011.
- [2] H. Ju and R. Zhang, "A novel mode switching scheme utilizing random beamforming for opportunistic energy harvesting," *IEEE Trans. Wireless Commun.*, vol. 13, no. 4, pp. 2150–2162, Apr. 2014.
- [3] T. Le, K. Mayaram, and T. Fiez, "Efficient far-field radio frequency energy harvesting for passively powered sensor networks," *IEEE J. Solid-State Circuits*, vol. 43, no. 5, pp. 1287–1302, May 2008.
- [4] M. T. Penella-Lopez and M. Gasulla-Fornier, *Powering Autonomous Sensors: An Integral Approach with Focus on Solar and RF Energy Harvesting*. Springer, 2011.
- [5] A. Bletsas, A. Khisti, D. Reed, and A. Lippman, "A simple cooperative diversity method based on network path selection," *IEEE J. Select. Area Commun.*, vol. 24, no. 3, pp. 659–673, Mar. 2006.
- [6] E. Beres and R. Adve, "On selection cooperation in distributed networks," in *Proc. 2006 Conference on Information Sciences and Systems (CISS 2006)*, Mar. 2006.
- [7] K.-H. Liu, "Selection cooperation using RF energy harvesting relays with finite energy buffer," in *Proc. IEEE WCNC*, Istanbul, Turkey, Apr. 6–9 2014.
- [8] Z. Ding, I. Krikidis, B. Sharif, and H. V. Poor, "Wireless information and power transfer in cooperative networks with spatially random relays," *IEEE Trans. Wireless Commun.*, to appear.
- [9] Z. Ding and H. V. Poor, "Energy harvesting cooperative networks: Is the max-min criterion still diversity-optimal?" submitted for review.